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Simulated effects of water table and irrigation scheduling as factors in cotton production

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Summary. Irrigation is essential for economic production of some crops in semiarid climates. Benefits from irrigation may be partially offset by detrimental effects of rising water tables and salinization. Drainage systems are usually installed when the water table rises to the root zone, but installation of a drainage system and safe disposal of drainage water are expensive. The long-term consequences of a high saline water table on crop production, particularly as related to irrigation scheduling, has not been firmly established. A multiseasonal transient state model, known as the modified van Genuchten-Hanks model, was used to simulate cotton (*Gossypium hirsutum* L.) production using a three or four in-season irrigation schedule (3irr or 4irr) under both free drainage and water table conditions. Under drainage conditions, irrigation scheduling to avoid applying more water than the soil water-holding capacity during any irrigation event is important, whereas this factor is less important under water table conditions. "Excess" water during an irrigation causes a rise in the water table, but this water remains available for later crop use which lowers the water table. In the presence of a water table the simulations indicate, (1) higher yields are achieved by applying less irrigation during the crop season and more during the preirrigation for salt leaching purposes, (2) annual applied water must equal evapotranspiration to avoid long-term water table rise or depletion, and (3) high cotton yields can be achieved for several years even if the water table is saline and no drainage occurs if the irrigation water is low in salinity.

Agricultural production in arid and semiarid regions of the world has been greatly increased by developing irrigation projects. The benefits of irrigation projects have been partially offset by the detrimental effects of rising water tables and salinization. The water percolating below the root zone moves downward until it reaches the saturated zone and causes the water table to rise. The percolating water is frequently saline because the salts in the irrigation water are concentrated by evapotranspiration (ET) and some minerals in the profile may dissolve. Depending on chemical constituents in the irrigation water, some salt may also precipitate as the soil solution becomes concentrated by ET.

As water tables approach the soil surface, crop yields may be reduced by poor soil aeration and/or high salinity in the root zone. Installation of a drainage system to keep the water table from becoming too shallow and to leach salts is commonly considered to be essential for long-term productivity. Drainage systems have the drawbacks of being expensive to install and producing a surface supply of saline water which must be properly disposed. In some cases, such as the San Joaquin Valley of California, the drainage waters may also be laden with biologically toxic chemicals such as selenium which makes safe disposal difficult and expensive (Letey et al. 1986).

Knapp et al. (1990) presented a dynamic optimization model for irrigation investment and management under limited drainage conditions. Starting with a deep water table and optimal management, deep percolation is progressively reduced through time by a combination of improved irrigation systems and reduced water applications. This delays the water table build-up and postpones drainage costs. The model used to compute crop-water production functions for this study is only valid if deep percolation water is removed by a drainage system when the water table is near the surface. The consequence of continued irrigation without installing a drainage system under high water table conditions could not be determined.

Grimes et al. (1984) showed that substantial contributions to the seasonal cotton crop ET can come from a shallow saline groundwater. Therefore, the costs of installing a drainage system may be avoided by altering irrigation management and allowing the crop to draw water from the water table. Hanson et al. (1984) discussed management of irrigated lands which are underlain with

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a high water table. The beneficial effects of water and the detrimental effects of salts from a water table on crop production have not been completely quantified.

Irrigation scheduling and the total applied water affect the soil water content and potential utilization of a water table. The effects of these variables should be ascertained in order to manage the water table efficiently. Modeling crop production can provide a rapid, relatively inexpensive means of estimating the effects of various irrigation management practices on crop production under a variety of climatic and physical conditions.

The goal of this paper was to examine the effects of a water table and irrigation scheduling on cotton (*Gossypium Hirsutum* L.) production. To do this, a multi-seasonal transient state model was used to simulate crop production under various irrigation management regimes. To isolate the contributions of the high water table on crop yields, comparable simulations were run with and without drainage. The model used for these simulations is referred to as the modified van Genuchten-Hanks model (V-H model) (Cardon and Letey 1992b).

Description of the model

Cardon and Letey (1992a, b) compared the merits of two soil-plant-atmospheric continuum models; one developed by M. Th. van Genuchten and another by R. J. Hank and Colleagues (van Genuchten 1987; Nimah and Hanks 1973; Childs and Hanks 1975; Torres and Hanks 1989). Based upon the relative merits of the van Genuchten and the Hanks models, Cardon and Letey (1992b) formulated the modified van Genuchten-Hanks (V-H) model. Model prediction compared reasonably well to results from a field experiment which had irrigation water salinities and amounts as variables (Cardon and Letey 1992b) and to a greenhouse experiment designed to have a high water table (Cardon and Letey 1992c).

The V-H model uses van Genuchten's water extraction term. When matric and osmotic potential effects are present this term is:

$$S(z, t) = \frac{S_m(z, t)}{1 + \left[\dfrac{a \cdot h + \pi}{\pi_{50}}\right]^3} \tag{1}$$

where $S_m(z, t)$ is the potential extraction rate,

$$S_m(z, t) = \frac{T_p(t)}{L(z, t)} \tag{2}$$

$T_p(t)$ is the potential transpiration, $L(z, t)$ is the rooting length, π is the osmotic potential, h is the matric potential, π_{50} and h_{50} are the potentials at which 50% reduction in yields occur for a specific crop and "a" is the ratio of π_{50} and h_{50}. $S_m(z, t)$ is adjusted at varying depths to account for root distribution.

$S_m(z, t)$ in (Eq. (2)) is affected by root distribution and depth of root growth. The V-H model as used assumed a root density distribution of 40%, 30%, 20%, 10% per quarter of root depth from top to bottom of the rooting depth (L). "L" as a function of time is specified by the modeler. The model allows feedback whereby L is adjusted to account for matric and/or osmotic stress, as well as restricting roots from growing below the water table level. Bingham et al. (1970) demonstrated that zonal salinization in the root zone caused preferential root growth and water uptake to occur in areas of low salinity. The modeler can specify any root distribution, but the V-H model does not account for preferential root growth other than specified by the modeler.

The summed water extraction term over z and t, $\Sigma S(z, t)$, is related to crop yields in a linear relationship as follows:

$$\frac{\Sigma S(z, t)}{\Sigma S_m(z, t)} = \frac{Y}{Y_m} \tag{3}$$

where Y is the dry matter production and Y_m is the maximum dry matter production without salt or water stress. The relationship between cotton lint yield, Y^l, and dry matter is (Letey and Dinar 1986)

$$Y^l = -0.361 + 0.194\, Y - 0.00489\, Y^2 \tag{4}$$

Results in this paper will be reported on the basis of dry matter production because the effects of osmotic or matric potential stress are greater on dry matter than on lint yields. Thus the effects of stress are magnified in the results as reported.

The V-H model uses a soil hydraulic properties function developed by Hutson and Cass (1987) which can be used over the entire soil water content range, including saturation. The parameter values of the soil hydraulic properties used in the simulations are presented in Table 1. The modified V-H model is one-dimensional in space and assumes uniform irrigation. It can not simultaneously simulate nonuniform irrigation over a cropped field.

The simulation is started by specifying an initial salt and water distribution in the soil. Infiltration from irrigation is simulated by the Hanks model and provides distributions of salt and water after irrigation. These distributions are then used by the modified van Genuchten model which simulates water uptake by the crop during the period between irrigations. Salt and water distributions in the soil as a function of time are also computed by the van Genuchten model. These distributions then become the initial conditions for the Hanks model at the time of the next irrigation. This cycle is continued throughout the crop season. The final salt and water distribution from the

Table 1. Parameter values of soil hydraulic properties used in the simulations

Name	Symbol	Value
Campbell parameters:	b	3.26
	B	8.45
	ψ_e	−1.40 kPa
Hutson and Cass parameters:	θ_i	0.42
	ψ_i	−2.23 kPa
	K_{sat}	0.89 cm/h
	θ_{sat}	0.48

crop season serves as the initial conditions for the Hanks evaporation routine used during the non-crop season. Distributions generated by the Hanks evaporation routine between precipitation events (infiltration by Hanks model) are used as the initial conditions for the next precipitation event. The final salt and water distributions generated during the non-cropping season are specified as the initial conditions for the subsequent crop season. The sequencing of these events can be continued for multi-seasonal analysis.

Input variables are amount, time, and salinity of irrigation water application and/or precipitation. The value of $S_m(z, t)$ (Eq. 2) must be specified for a given time period. $S_m(z, t)$ equals potential transpiration (transpiration that would occur without water or salt stress), but potential ET (PET) rather than transpiration is usually known so the computations are based on PET values. The PET was taken as the climatic evapotranspiration (ET_0), times a crop coefficient, K_{cr}, which varies with crop and stage of plant growth. Values of K_{cr} must be empirically established.

The simulations in this study were for climatic and cropping conditions typical of the San Joaquin Valley, California. The seasonally variable ET_0 and crop coefficient values were taken from Letey and Vaux (1985). Averages of these values were used for each transpiration period between irrigations and are listed in Table 2. Precipitation, which occurs mostly in the winter months, was chosen to be equal to the long-term average between Mendota and Westside, California. During the winter, monthly average precipitation was applied in one event. In reality, precipitation occurs at random intervals and with random magnitudes; but except under extreme conditions, the effects of these random fluctuations would be expected to be averaged for the non-crop season. During the growing season, precipitation was assumed to be negligible.

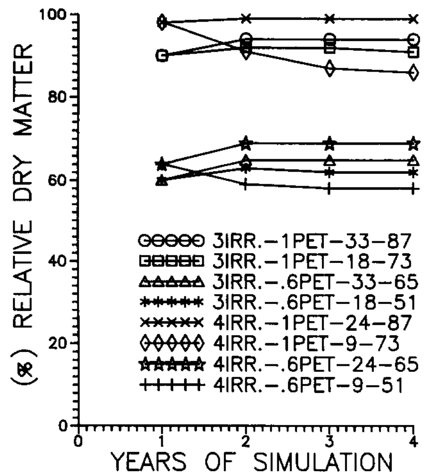

Fig. 1. Relative dry matter yields for cotton simulations with a free drainage boundary condition. Encoded in the legend is the irrigation schedule, the amount of in-season irrigation, the amount of preirrigation, and the total applied water

Table 2. ET_0, K_{cr}, and rooting depth of cotton for various simulated transpiration periods

Transpiration period (dates)	ET_0 (cm/day)	K_{cr}	Root depth max. (L) (cm)
3 irr Schedule			
April 15–June 15	0.540	0.36	101
June 16–July 15	0.660	1.00	131
July 16–August 15	0.623	1.25	142
August 16–October 15	0.448	0.93	180
4 irr Schedule			
April 15–June 15	0.540	0.36	101
June 16–July 11	0.660	1.00	131
July 12–August 4	0.625	1.19	141
August 5–September 6	0.511	1.05	166
September 7–October 15	0.448	0.93	180

Irrigation schedule with drainage

Cotton growth was simulated for four years using the lower boundary layer (250 cm depth) set at −10 kPa matric potential, and two irrigation schedules. The schedules were four and three irrigations during the growing season (Table 2). The initial volumetric water content and matric potential throughout the profile were respectively 0.26 and −10 kPa. The initial salt distribution was 0.4 dS m^{-1} from 0- to 125-cm depth, this linearly increased to 9.0 dS m^{-1} at a depth of 150 cm, and then remained constant at 9.0 dS m^{-1} to 250 cm (the lower boundary layer).

All irrigation waters had EC equal to 0.4 dS/m. In-season irrigations equal to 1.0 or 0.6 PET for the period between irrigations were applied. The preirrigation amount accounted for ET of the crop following the last irrigation and evaporation and precipitation during the non-crop season. The four irrigation (4 irr) schedule resulted in more water application during the growing season then the 3 irr schedule. Preirrigations were 24 or 9 cm for the 4 irr schedule, and 33 or 18 cm for the 3 irr schedule. The difference in preirrigations between the two schedules provided for the same total amount of applied water during a year for the two schedules. Preirrigations were only applied during the second and succeeding years of the simulations because the initial soil water condition for the first year was field capacity in each case.

The relative dry matter yields for cotton over four years are illustrated in Fig. 1. Each simulation is encoded in the legend as follows. The first number is the number of irrigations, the second number is the percentage of PET the cotton received during the growing season, the third number is the amount of preirrigation (cm), and the final number is the total applied water (AW (cm)) during the year.

All 1 PET treatments have higher yields then the 0.6 PET treatments. The 4 irr schedule produced higher yield than the 3 irr schedule during the first season when all profiles started with the same water content. This occurred because more water was applied and a shorter drying time between irrigations occurred for the 4 irr schedule than the 3 irr schedule. After the first year the yields were consistently related to total amount of applied

Table 3. Deep percolation and evaporation values from simulations with free drainage

	Deep percolation (cm)				Evaporation (cm)			
	*Y*1	*Y*2	*Y*3	*Y*4	*Y*1	*Y*2	*Y*3	*Y*4
3 Irrigations								
1 PET-33-87	4	16	17	17	10	11	11	11
1 PET-18-73	4	1	3	3	10	11	11	11
0.6 PET-33-65	4	16	15	15	10	10	10	10
0.6 PET-18-51	4	1	1	1	10	10	10	10
4 Irrigations								
1 PET-24-87	3	9	10	10	12	13	13	13
1 PET-9-73	3	−3	−2	0	12	13	15	15
0.6 PET-24-65	4	7	7	7	10	10	10	10
0.6 PET-9-51	4	−3	−2	−2	10	11	11	13

water in the order of 87 > 73 > 65 > 51 cm. However, the number of irrigations and preirrigation amounts did affect the yields for a given total amount of applied water.

When 87 cm of water were applied the 4 irr schedule had higher yields than the 3 irr schedule. The deep percolation (DP) and evaporation amounts of the various simulations are presented in Table 3. Much of the 3 irr and 33 cm preirrigation water was lost as DP, primarily during the preirrigation. The 4 irr schedule lost less water through DP and only slightly more by evaporation; thus more was available for transpiration than for the 3 irr schedule. The difference in leaching potential between the 33 cm and 24 cm preirrigations was less important to crop yields than was the increased water availability during the season of the 4 irr schedule.

With the application of 73 cm, the 3 irr had higher yields then the 4 irr schedule. Examination of data in Table 3 reveals that the 3 irr scenario lost a little water from the soil as DP, and with the 4 irr simulation, water flowed up into the profile. The 4 irr schedule evaporated slightly more than the 3 irr schedule. Figures 2 and 3 show the salt distribution with depth for the 4 irr and 3 irr schedules at the end of the growing season. The salt concentration was adjusted to a common soil water content (saturation) and then expressed as the EC of that solution ($EC_{sat} = EC \cdot \theta/\theta_{sat}$). It is observed that the upward flow of water at the boundary layer and the increased evaporation of 4 irr schedule brought more salts into the profile than the 3 irr schedule. This salt accumulation is responsible for increased osmotic stress and the slight reduction in yields between the two irrigation schedules.

Simulations which applied 65 cm can be explained in an analogous fashion to those which received 87 cm. Much of the high preirrigation was lost to DP. Here, however, the 65 cm simulations have lower yields than those which received 87 cm because of the increased matric stress on crops due to deficit irrigation.

Simulations which applied 51 cm of water can be explained in a similar fashion to those which received 73 cm. Figure 4 shows the EC_{sat} distribution with depth of the 4 irr schedule. Comparison of Figs. 2 and 4 reveal that the 73 cm simulation leached the salts more effectively

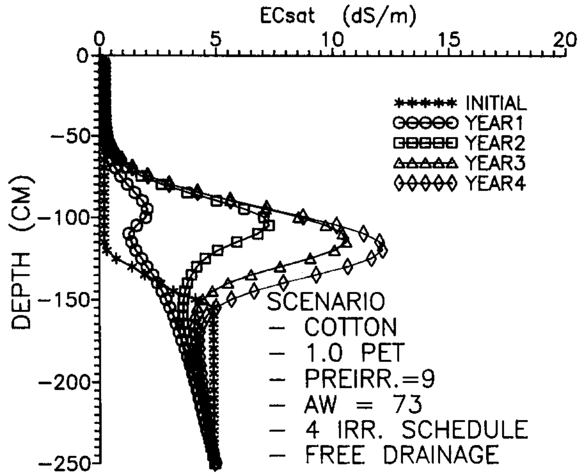

Fig. 2. The saturated electrical conductivity at the end of the growing season for the specified conditions

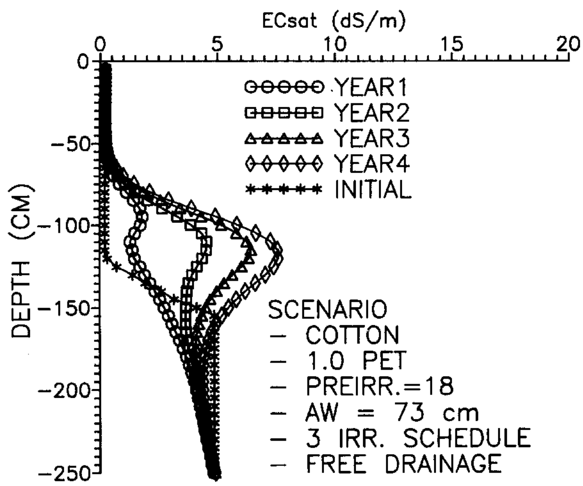

Fig. 3. The saturated electrical conductivity at the end of the growing season for the specified conditions

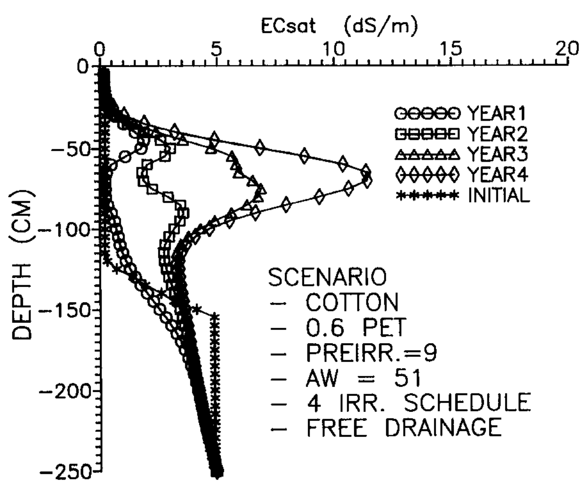

Fig. 4. The saturated electrical conductivity at the end of the growing season for the specified conditions

than the 51 cm simulation. The diminished leaching potential of 51 cm simulation is primarily responsible for the increased salinity effects and subsequent decrease in yields.

In summary, scheduling as well as annual total amount of irrigation is important in cotton production. In particular an irrigation which applies more water than can be stored in the profile, such as a large preirrigation, results in DP which does not contribute to plant growth. Note that for the 3 irr schedule there was almost as much DP from the 65 as the 87 cm annual application because both had the identical high preirrigation from which the DP occurred (Table 3). Unfortunately infiltration rates are typically high after plowing and other tillage operations prior to the preirrigation and conducive to large water intake. Infiltration rates typically decrease as the season progresses leading to lower intake during in-season irrigations.

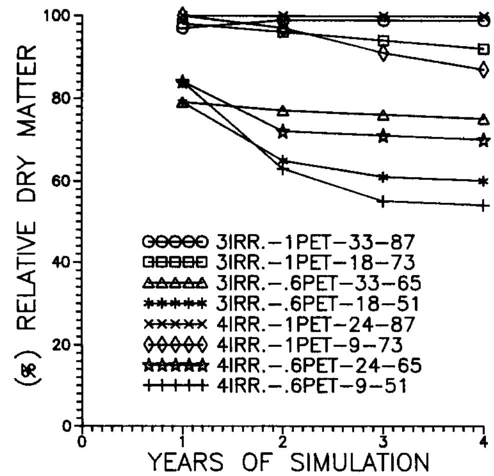

Fig. 5. Relative dry matter yields for cotton simulations with a water table boundary condition. The legend is encoded as Fig. 1

Irrigation schedule with a water table

Four years of cotton production on lands underlain with a saline high water table were simulated using the same irrigation strategies as outlined in the previous section. In this case the lower boundary layer was set to be impermeable so no drainage could occur. From the surface to the water table the soil was initially at a volumetric water content of 0.26 and a salinity of 0.4 dS/m. The water table was initially at a depth of 150 cm, volumetric water content of 0.48 (saturation) and a salinity of 9.0 dS/m.

The relative dry matter yields for four years of simulated cotton growth in the presence of a water table are presented in Fig. 5. The 4 irr schedule produced higher yields the first year than the 3 irr schedule because more total water was applied during the season and a shorter drying time occurred between irrigations. After the first year, 3 irr had higher yields than 4 irr for a given annual AW except for 87 cm of AW where the yields were almost 100% in each case. For AW less than 87 cm and following preirrigation, the 4 irr schedule had larger maximum salt concentration which was positioned higher in the rooting zone than the 3 irr schedule because the larger preirrigation of the latter schedule leached the salt deeper.

The results suggest a number of points concerning irrigation management in areas which are underlain with a saline high water table. First, in areas which received 87 cm annual irrigation which, along with the precipitation, provided for crop ET and non-crop season evaporation, the irrigation schedule was relatively unimportant. Under this condition, maximum cotton yields could be maintained for at least four years without any drainage. Second, as total applied water decreased, higher yields could be achieved by applying less irrigation during the crop season and more during the preirrigation. Some of the water deficit during the growing season could be compensated by the water table. The water that would have been used during the growing season could then be used to leach salts from the rooting zone during the preirrigation. Deficit irrigation is not a long term strategy because the water table becomes depleted and no longer

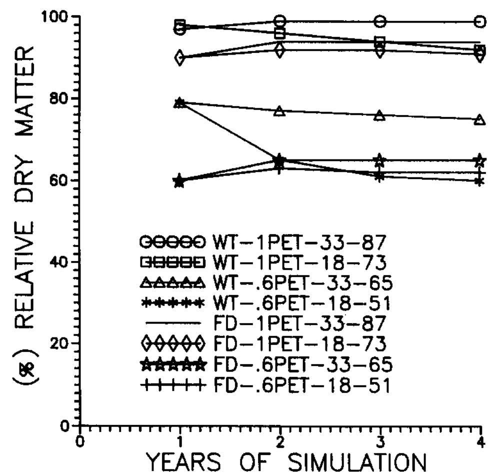

Fig. 6. Relative dry matter yields for cotton simulations which used the three in-season irrigation schedule. Encoded in the legend is the boundary condition, the amount of in-season irrigation, the amount of preirrigation, and the total applied water

becomes a source of water for the crop. Note the decrease in yield with time for irrigations which applied less than 87 cm of water (Fig. 5). No simulations were run with water applications greater than 87 cm because the water table would then rise and the crop would suffer from inadequate aeration.

Water table vs. free drainage

To isolate the contributions of the water table on cotton yields, water table (WT) and free drainage (FD) simulations which had the same annual applied water and irrigation schedule will be compared. The relative dry matter for cotton yields using the 3 irr schedule are shown in Fig. 6. Since yields from the 4 irr schedule follow a trend analogous to that found in Fig. 6 only the 3 irr schedule's yields will be presented.

Note for the first two years the WT simulations had higher yields than the FD simulations in each case. This result is associated with the initial conditions whereby the WT had more water than the FD simulations in the profile at depths greater than 150 cm. This additional water was responsible for the higher yields of the WT simulations.

WT had higher yields than FD with 87 cm AW because approximately half of the FD preirrigation was lost to deep percolation (Table 3). The impermeable layer in the WT simulations retained the preirrigation water that would have been lost as DP and this stored water was available during the crop season.

For simulations which had 73 cm AW, the WT had higher yields than the FD, but the difference between yields decreased with time. Little water was lost to DP for FD and 73 cm AW (Table 3). Therefore, the WT simulation retained little more water than the FD, and the water table became depleted of water with time. As water and salt move up from the water table the osmotic and matric effects increase and yields decrease.

The simulations which had 65 cm AW follow a trend analogous to those of 87 cm AW, however, differences in yields between the WT and FD simulations are greater for the 65 cm AW. The 87 cm simulations had less water stress than the 65 cm simulations due to their larger in-season irrigations. As water stress increases, storage of the preirrigation in the water table becomes more important in maintaining crop yields. Table 3 shows that the 65 cm FD simulation lost similar amounts of water as the 87 cm FD simulation. The loss of water to DP coupled with the smaller in-season irrigations caused a major reduction in yields in the 65 cm FD simulations.

The simulations which had 51 cm AW behaved similarly to the simulations which applied 73 cm except that after the second year the yields were slightly higher for FD than WT. Figures 7 and 8 illustrate the EC_{sat} distributions for the FD and WT simulations after application of the preirrigation. The WT simulation has significantly more salt in the profile than does the FD simulation. As the water table was used by the crop, salts were transported upward in the profile. Eventually the detrimental effects of salt buildup dominated over the beneficial effects of the retained water. For the simulation which applied 51 cm this happened after the second year.

Comparison of WT and FD simulations reveals that water tables can help maintain crop yields, particularly if any irrigation results in considerable DP under FD. In the absence of DP, the beneficial effects of WT cannot be sustained because the WT becomes depleted and salts move up into the root zone. The beneficial effects of WT cannot be sustained when total irrigation exceeds ET because of WT rise (a condition not simulated). All of the simulations reported here were for uniform irrigation. Bradford et al. (1991) addressed nonuniform water application under a WT condition. Under FD conditions, nonuniformity of irrigation would result in significantly more DP and consequently lower yields than for the uniform conditions depicted in this report.

Models cannot completely reproduce all of the complex interactions which occur in nature so the quantitative results may not be precise. Nevertheless, models are useful in identifying possible mechanistic trends and long-term effects and providing guidance in designing experiments.

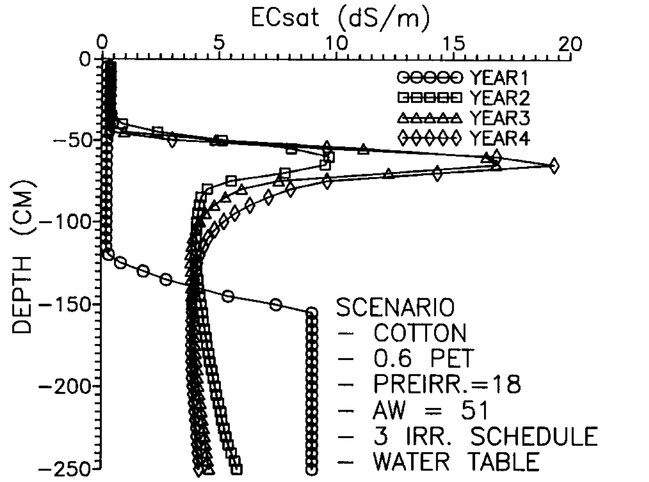

Fig. 7. The saturated electrical conductivity after application of the preirrigation for the specified conditions

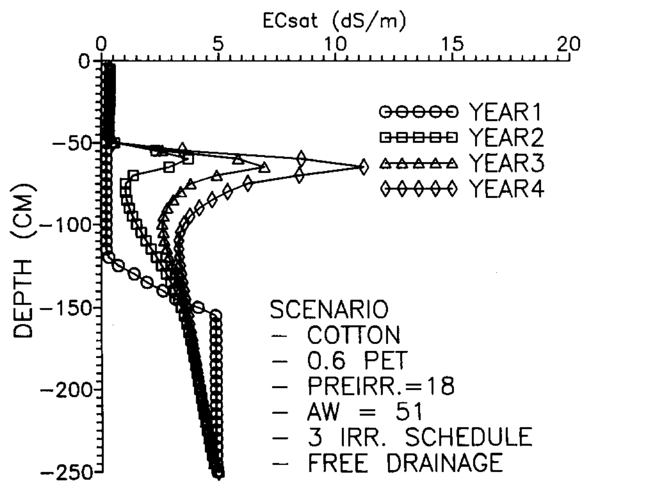

Fig. 8. The saturated electrical conductivity after application of the preirrigation for the specified conditions

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